Review on Phase Change Materials in Different Solar Gadgets

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Abstract — Solar energy is by far the most attractive alternative energy sources for the future. But the main problem of solar energy is its intermittent nature. However, solar drying is in practice since time immemorable for preservation of food and agricultural crops. This was done particularly by open sun drying under the open to sky. This process has several disadvantages like spoilage of product due to adverse climatic conditions like rain, wind, moist, dust, loss of material due to birds and animals. Solar cabinet dryer with heat storage system become popular due to considerable deduction of drying time and significant improvement of product. Solar dryer for domestic as well as industrial usage could be an effective alternative of saving conventional energy. The provision of heat storage material in solar cabinet dryer such as gravels, sand, iron scraps, etc. which can store the heat energy during sunshine hours and provide the heat during off sunshine hours. By the introduction of heat storage system in solar dryer, additional drying hours could make available.

Recently, the incorporation of PCM in different applications has grown interest to the researcher. This paper is a compilation of much of practical information on few selected PCMs used in different solar systems. A review of solar air heating systems with storage units include space heating systems, greenhouses with various thermal storage materials, solar air heaters integrated with various storage materials and heat transfer studies on air as a heat transfer fluid, have been carried out and it will also help to provide a variety of designs to store solar thermal energy using PCMs.

Keywords — Solar drying, phase change medium, latent heat storage, sensible heat storage.

I. INTRODUCTION

Since solar radiation is an inherently time-dependent energy resource, storage of energy is essential if solar is to meet energy needs at night or during daytime periods of cloud cover and make a significant contribution to total energy needs. Since radiant energy can be converted into a variety of forms and feasible to be stored such as; thermal energy, chemical energy, kinetic energy, or potential energy. Generally, the choice of the storage media is related to the end use of the energy and the process employed to meet this application.

In many cases continuous drying is preferred. However, solar cabinet dryer is operated only during day time for 7 to 8 h. The conventional source of energy is used to continue the drying after sun set. Thermal storage system could be coupled with the solar dryer to improve its efficiency, operating hours of solar dryers. This could also save conventional source of energy. In view of the above, there was need to develop and study solar heat storage system for drying vegetable.

The storage of thermal energy as latent heat of fusion has attractive features over the sensible heat due to its high storage density and isothermal nature of storage process at melting temperature. The phase change from solid to liquid or vice-versa is preferred because the operating pressure is lower than liquid to gas or solid to gas phase change. In practice several PCMs are known, such as: paraffin’s, fatty-acids, organic and inorganic salt hydrates, organic and inorganic eutectic compounds.

The PCM to be used in the design of any thermal storage systems should have high latent heat of fusion, high heat conductivity (more than 0.5 W/m°C), material’s melting temperature should be in the functional interval if it stores solar energy, congruent melting, minimal supercooling, chemical stability, economic efficiency and aspects of environmental protection.

Organic and Inorganic PCM and its properties: A comparison of the advantages and disadvantages of organic and inorganic is shown in Table 1.
TABLE I
Comparison of organic and inorganic materials for heat storage [1], [2]

<table>
<thead>
<tr>
<th>Organic</th>
<th>Inorganic</th>
</tr>
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<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Advantages</strong></td>
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<tr>
<td>Chemical and thermal stability, Suffer little or no supercooling, Non-corrosives, Non-toxic, High heat of fusion and low vapour pressure</td>
<td>High heat of fusion, Good thermal conductivity, Cheap and non-flammable</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>Low thermal conductivity, High changes in volumes on phase change, Inflammability, Lower phase change enthalpy</td>
<td>Phase decomposition and suffer from loss of hydrate, lack of thermal stability, Supercooling, Corrosion</td>
</tr>
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The PCM to be used in the design of any thermal storage systems should pass desirable thermophysical, kinetics and chemical properties which are given in Table 2.

TABLE II
Main desirable properties of phase change materials [2], [3]

| Thermal properties       | Suitable phase-transition temperature, High latent heat of transition, High thermal conductivity in both liquid and solid phases, Good heat transfer |
| Physical properties      | Favorable phase equilibrium, High density, Small volume change, Low vapor pressure |
| Kinetic properties       | No supercooling, Sufficient crystallization rate |
| Chemical properties      | Long-term chemical stability, Compatibility with materials of construction, No toxicity, No fire hazard |
| Economic Properties      | Abundant, Available, Cost effective |

The ideal PCM to be used for latent heat storage system must meet following requirements: high sensitive heat capacity and heat of fusion; stable composition; high density and heat conductivity; chemical inert; non-toxic and non-inflammable; reasonable and inexpensive.

In the nature, the salt hydrates, paraffin and paraffin waxes, fatty acids and some other compounds have high latent heat of fusion in the temperature range from 30°C to 80°C that is interesting for solar applications.

Use of PCM in Greenhouses:
Mehmet [4] designed a system consists of a solar collector (30 m²) connected to a cylindrical latent heat storage tank that was filled with 1090 kg encapsulated PCM (Ca₃Cl₂·6H₂O) linked to a solar powered heat pump used for space heating, this system works with two modes, one when no solar energy or weak, the cold water goes to the storage unit to extract the heat, while the other mode when there is a solar energy and the space heating load is zero the hot water circulated between the collector and PCM tank.

Alkilani [5] reported that phase change material have been used in greenhouses to storing the solar thermal energy for curing and drying process and plant production [6]. When the ambient temperature drops below the phase change temperature, the PCMs solidify, releasing stored heat. PCMs can store 5–14 times more heat per unit volume than conventional storage materials and can also be more long term.

Kern and Aldrich [7] utilized 1650 kg of CaCl₂·6H₂O in aerosol cans each weighing 0.74 kg was used to investigate energy storage possibilities both inside and outside a 36 m² ground area of greenhouse. Fiber glass PCM cans were placed in a store with 22.86 mm spacing and two stores containing different amounts of PCM was used, one inside and the other outside the greenhouse. While the energy storage unit inside the greenhouse absorbed the energy of warm air from the ridge of the greenhouse during the daytime, the direction of air flow was reversed for the energy releasing process at night.

Nishina and Takakura [8] used Na₂SO₄·10H₂O with some additives to prevent phase separation and degradation for heating a greenhouse in Japan. This study concluded that 40–60% of the latent heat potential of the PCM was realized, which indicated that almost half of the PCM was not used efficiently during the energy exchange processes.

Takakura and Nishina [9] tested polyethylene glycol and CaCl₂·6H₂O as PCMs in greenhouse heating for 7.2 m² ground area. They
compared conventional greenhouses with PCM storage type greenhouses. The efficiency of the greenhouse with PCM storage integrated with solar collector was 59% and able to maintain 8°C inside the greenhouse at night, when the outside temperature dropped to −0.6°C. A microcomputer control system has been developed in order to establish more accurate and more sophisticated control for solar greenhouse systems.

In a design and experimentation study by Baille and Boulard [10] and Boulard et al. [11] CaCl₂·6H₂O melting at 21°C was utilized in a greenhouse with 176 m² ground area, double polycarbonate-cover and forced ventilation

Ozturk [12] presented a seasonal thermal energy storage using paraffin wax as a PCM with the latent heat storage technique was attempted to heat the greenhouse of 180 m² floor area.

Kurklu [13] has summarized work on greenhouses using PCM. CaCl₂·6H₂O and Na₂SO₄·10H₂O have been widely used because of low cost and high heat storage capacity with suitable melting point, but supercooling and sensitivity towards moisture are serious disadvantages for long-term use.

**Use of PCM in Solar Air Heaters:**

Fath[14], Enibe [15], Alkalani[16] and many other scientists have used paraffin wax as a PCM for thermal storage in solar air heating and found that higher thermal energy storage density of these materials gives better performance for drying as compared to sensible heat storage material.

Alkalani [5] designed, fabricated and performed indoor testing of solar air heater integrated with PCM Experimental results indicated that the charging time was reduced by approximately 70% when used the paraffin wax-aluminum composite. The thermal storage efficiency reached the maximum magnitudes 71.9 and 77.18% at mass flow rates 0.05 and 0.07 kg sec⁻¹ for pure paraffin wax and the compound respectively. The results indicated that the heater filled with PMCs with 51 and 43°C melting temperatures gives the best performance, otherwise the system daily average efficiency varies between 27 and 63% depending on the PCM melting temperature, solar intensity and system air flow resistance.

Krishnananth [17] conducted experimental study on double pass solar air heater with PCM as thermal storage system. Paraffin wax is used as a thermal storage medium. The performance of this heater was studied for different configurations. The solar heater integrated with thermal storage delivered comparatively high temperature. The efficiency of the air heater integrated with thermal storage was also higher than the air heater without thermal storage system. The study concluded that

the presence of the thermal storage medium at the absorber plate is the best configuration.

Fath [18] used a thermosyphon solar air heater with a series of packed tubes containing a PCM with different melting temperatures of 61, 51, 43 and 32°C. The tubes were arranged parallel to each other in order to make a flat-plate-style configuration with air flowing over and under them simultaneously. This work will address packed beds of encapsulated PCM in the spherical capsules system which is one of the most effective and compact latent thermal energy systems.

Saxena [19] made an efforts to enhance the heat transfer rate and to improve the efficiency of simple fabricated solar air heater. “Granular carbon”, has introduced as a long term heat absorbing media inside solar heater. The thermal performance evaluation of solar heater has been carried out on four different configurations by operating it on natural and forced convection. The thermal performance of all the new configurations was found better in comparison of conventional solar air heater on both natural and forced convection.

Badgujar [20] A forced convection with desiccant integrated solar dryer has been built and tested. The system is operated in two modes, sunshine hours and off sunshine hours. During sun shine hours the hot air from the flat plate collectors is forced to the drying chamber for drying the product and simultaneously the desiccant bed receives solar radiation directly and through the reflected mirror. In the off sunshine hours, the dryer is operated by circulating the air inside the drying chamber through the desiccant bed by a reversible fan. The dryer is used to dry 20 kg of green peas and pineapple slices. The drying efficiency of the system varies between 48% and 59% and the pick-up efficiency varies between 25% and 60%, respectively.

Seshan Ram [21] A sophisticated solar tunnel dryer is designed and developed suitable for drying all kinds of agricultural produce, spices, marine products, etc. The developed model is preferred to be well utilized for solar drying applications for partial energy requirement during night hours. Hence, this can be considered as an important study of the present work. The study reveals that acetamide can be used as thermal energy storage material for applications like solar drying, where the temperature requirement is mostly below 80°C.

Stalin Josef [22] The design of Phase change material is that the spherical balls are shaped with cylindrical holes in the centre. Large numbers of balls are placed in the path of the air in which the air passes through them. During solar radiation, air gets heated and the remaining heat is stored by PCM which also gives heat back to air, thereby increasing the efficiency of the dryer and operating without
radiation.

Use of PCM in other devices
Farid et al. [23] studied the feasibility of cool storage using dimethyl sulfoxide (melting point 16.5°C) as a PCM in a rectangular container. Based on the experimental results and the model predictions, dimethyl sulfoxide can be used as a PCM for cool storage. The results also show that, cooling extraction period depends on the amount of solidified PCM. The cool extraction period was completed when the outlet air temperature from the PCM section reached at 25°C. This temperature is considered the highest temperature at which the human may feel comfortable.

Farid et al. [24] used paraffin wax (55°C) encapsulated in a thin metal container to replace the ceramic bricks. An electrical plate heater was fixed at the axis of each storage unit to provide low heat flux but sufficient to melt all the wax. During charging, PCM stores latent heat of melting, which is continuously discharged during the other periods. An electrical plate heater was fixed at the axis of each storage unit to provide low heat flux but sufficient to melt all the wax within 8 h. They concluded that latent heat storage systems could shift the peak-heating load.

Ramasamy and Sivaraman [25] conducted an experiment to enhance the productivity of the solar still with the help of LHTESS (Latent heat thermal energy storage sub-system). For experimentation and comparison purpose, a Cascade Solar Still with and without LHTESS were designed and constructed for water purification with a view of enhancing productivity. Solar still of the present study mainly consists of stepped absorber plate integrated with phase-change energy storage sub-system or LHTESS and single slope glass plate. This setup will be placed at an angle of 25° to the horizontal. Paraffin wax is used as LHTESS due to its feasible general and economic properties. The hourly productivity is slightly higher in case of solar still without LHTESS during sunny days. The disadvantages of phase change material is corrosion when in direct contact with metal piping or housings.

Solar cooking:
Ramadan et al. [26] designed a simple flat-plate solar cooker with focusing plane mirrors using energy storage materials. In his design, a jacket of sand (1/2 cm thick) around the cooking pot has improved the cooker performance tremendously. They concluded that six hours per day of cooking time have been recorded. Approximately three hours per day of indoor cooking has been achieved. Overall energy conversion efficiency up to 28.4% has been obtained. The possibility of using a PCM as a storage medium to obtain longer cooking periods was studied. A thin layer of the salt hydrate Ba(OH)₂·8H₂O was studied. A thin layer of the salt hydrate Ba(OH)₂·8H₂O

Sharma et al. [27] designed and developed a cylindrical PCM storage unit for a box-type solar cooker to cook the food in the late evening. Because this unit surrounds the cooking vessel, the rate of heat transfer between the PCM and the food is higher, and cooking can be faster. For this purpose, a PCM container to hold the cooking vessel was designed and fabricated. They reported that by using 2.0 kg of acetamide as a latent heat storage material, the second batch of food could be cooked if it is loaded before 3:30 P.M. during the winter season. They recommended that the melting temperature of a PCM should be between 105 and 110°C for evening cooking. Therefore, there was a need to identify a storage material with appropriate melting point and quantity, which can cook the food in the late evening. To store a larger quantity of heat in a PCM, more input solar radiation would be required.

Solar water heating systems:
Tiwari et al. [28] presented an analysis of PCM storage for a water heater by incorporating the effect of water flow through a parallel plate placed at the solid-liquid interface. In order to reduce the night heat losses from the exposed surface, a provision of covering the system by movable insulation was made. They concluded that the hot water (temperature 15–20°C > ambient air temperature) can remain throughout the day and night, and the fluctuations in water temperature decrease with an increase in the melted region of the PCM water heater.

Sharma et al. [29] designed, developed and performance evaluate of a latent heat storage unit for evening and morning hot water requirements, using a box type solar collector. Paraffin wax (m.p. 54°C) was used as a latent heat storage material and found that the performance of the latent heat storage unit in the system was very good to get the hot water in the desirable temperature range. Authors also reported that to get the hot water in the desirable temperature range more fins may be provided to increase the effectiveness of the storage unit.

Tarhan et al. [30] designed, developed and tested three trapezoidal built in storage solar water heaters to find the possible contributions of the PCM use in terms of the PCM types (i.e. myristic acid and lauric acid) and the location of the PCM storage units (i.e. together with absorbing plate and together with baffle plate) to the water temperature rise and drop characteristics in their tanks. Lauric acid, stored in a storage unit that was also used as a baffle plate, considerably reduced the peak temperatures during the trials but had small effects on the dip temperatures.
Sharma [31] summarized the investigation of the solar water heating system incorporating with Phase Change Materials (PCMs) and reported that Bansal and Buddhi [32] and many other scientists used PCMs in solar water heating systems and concluded that the inclusion of a PCM module in water tanks for domestic hot-water supply is a very promising technology. It would allow to have hot-water for longer periods of time even without exterior energy supply, or to use smaller tanks for the same purpose.

Tayeb [33] developed a system for domestic hot water using Na$_2$SO$_4$.10H$_2$O as a PCM and compared it with the simulation model that gives the optimum flow rate of the inlet water supply required to maintain the constant-temperature water at the outlet.

Hasan et al. [34] has investigated some fatty acids as PCMs for domestic water heating. They recommended that myristic acid, palmitic acid and stearic acid, with melting temperature between 50°C-70°C are the most promising PCMs for water heating.

Kaygusuz [35] had conducted an experimental and theoretical study to determine the performance of phase change energy storage materials for solar water heating systems. CaCl$_2$.6H$_2$O was used as PCM.

II. CONCLUSIONS

From this study it is concluded that the recent researches focused on the phase change materials (PCMs) as a storage materials, because of the higher thermal energy storage density of these materials in contrast of sensible heat storage materials. For a better thermal performance of solar air heater a phase change material with high latent heat and with large surface area for heat transfer is required. The researcher’s designs going to the integration between solar energy collection and thermal storage to reduce the heat loss, volume and system cost.

Paraffin wax is a good PCM for energy storage in latent heat storage system. It has a suitable transition temperature range of 58-60°C and a relatively high latent heat of 210 kJ/kg. In addition, it does not exhibit any subcooling. A simple tube-in-tube heat exchanger system can be used for energy storage with reasonable charging and discharging times and heat release rates.

In a near future, PCMs will be more and more incorporated in global energy management solutions as the stress for innovative low environmental-impact technologies, the overall negative effect of energy consumption on the environment, and the cost of energy will all necessarily increase.

REFERENCES

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